CFD Simulations of the IHF 13-Inch Nozzle Flow: 55º Sphere-Cone Model, Manufactured Fences and Gaps

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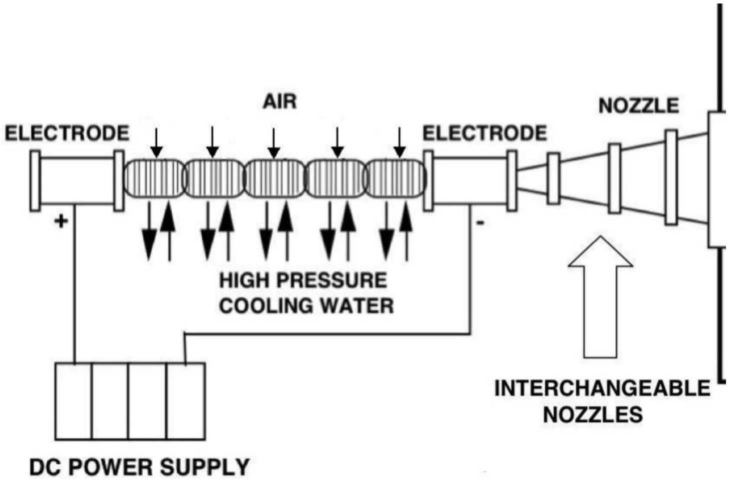
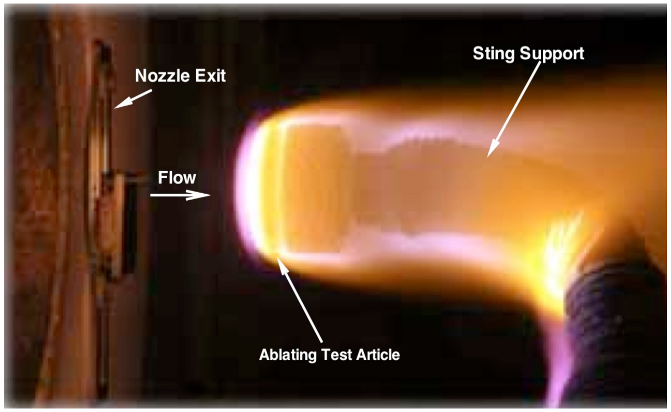
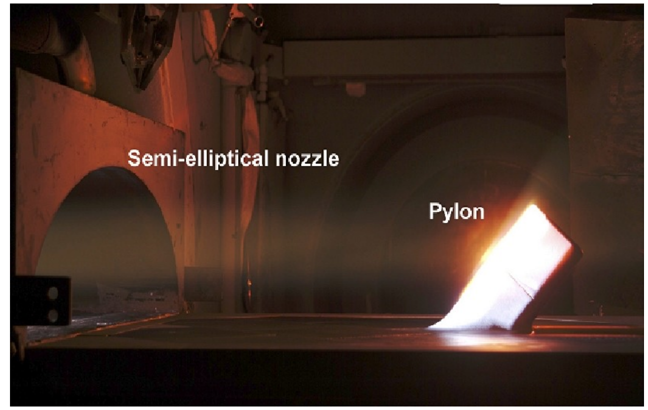
Introduction to Arc-Jets and Testing



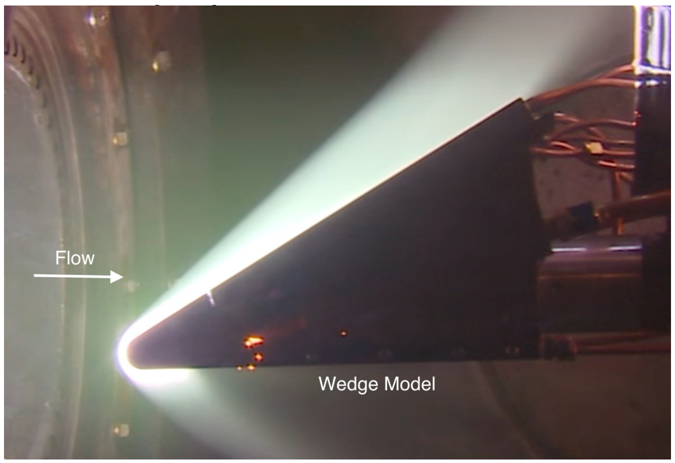
Arc-heater/nozzle sketch



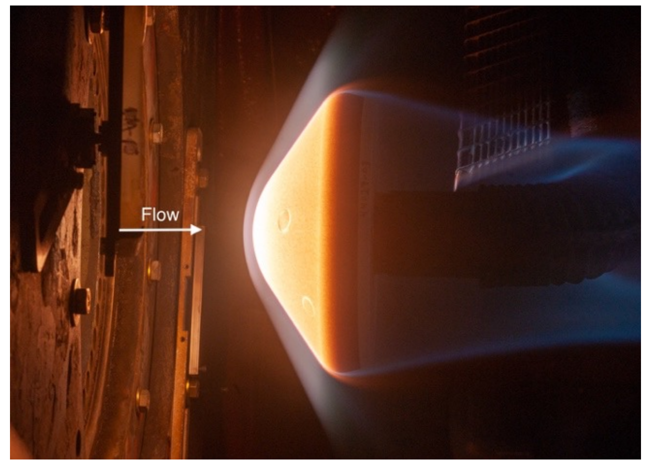
Stagnation coupon



IHF panel/pylon test



IHF wedge test



IHF sphere-cone model test

- Arc-jets are primary facilities to test the performance of thermal protection systems (TPS) in an aerothermodynamic heating environment
- Free jet test configuration with stagnation coupon or wedge models—conical nozzles
- Semi-free jet test configuration with panel test articles—semi-elliptical nozzles

A large-scale sphere-cone model, though similar to stagnation models, enables testing TPS materials in combinations of heat flux, pressure and shear different from those accessible in various stagnation and wedge tests

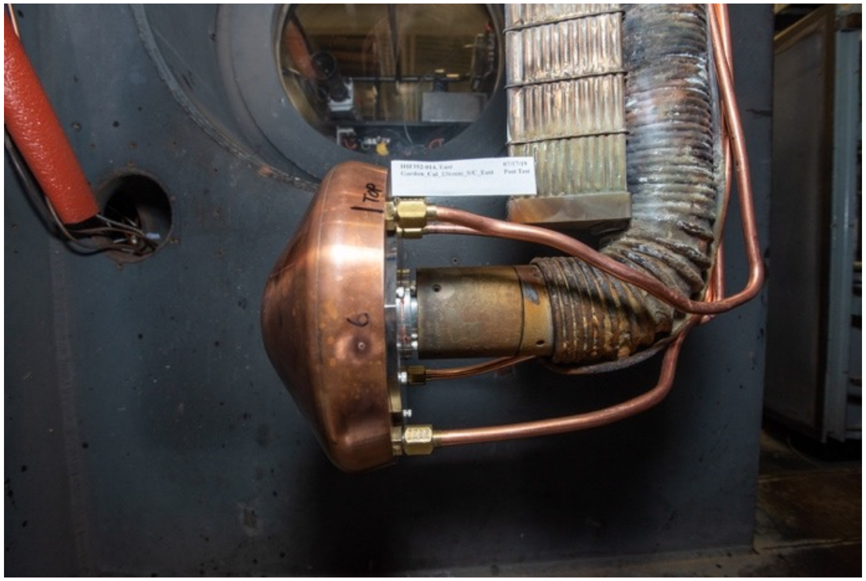
Objective and Scope

- Primary objective is to report computational analyses of tests in a high enthalpy arc-jet facility at NASA Ames Research Center
  - Orion TPS project conducted large-scale sphere-cone model tests in the 60-MW Interaction Heating Facility (2018, 2019)
  - 23.6-cm diameter, 55° sphere-cone models in a free jet downstream of the 33.0-cm diameter conical nozzle (IHF 13-inch nozzle)
  - Some of the sphere-cone models include surface features such as manufactured fences and gaps intended to simulate effects of differential recession (expected in flight)
  - Test calibration data were obtained using slug and Gardon gage calorimeters, and a sphere-cone calorimeter model with six Gardon heat flux gages and five pressure gages

- CFD simulations are performed to characterize the arc-jet test environment and its parameters consistent with the facility and calibration measurements and to provide surface quantities and input for material thermal response analyses
  - Several issues related to testing are addressed: diffuser flow capture, flow characterization based on the calorimeter data, effects of the model surface recession, and prediction of surface quantities for the models with surface features
  - Comparisons with available test data (55° sphere-cone calorimeter data, test photographs, HD video and IR camera images)

Calorimeter Models

IHF 13-Inch Nozzle Flow, IHF 345 and IHF 352 Tests

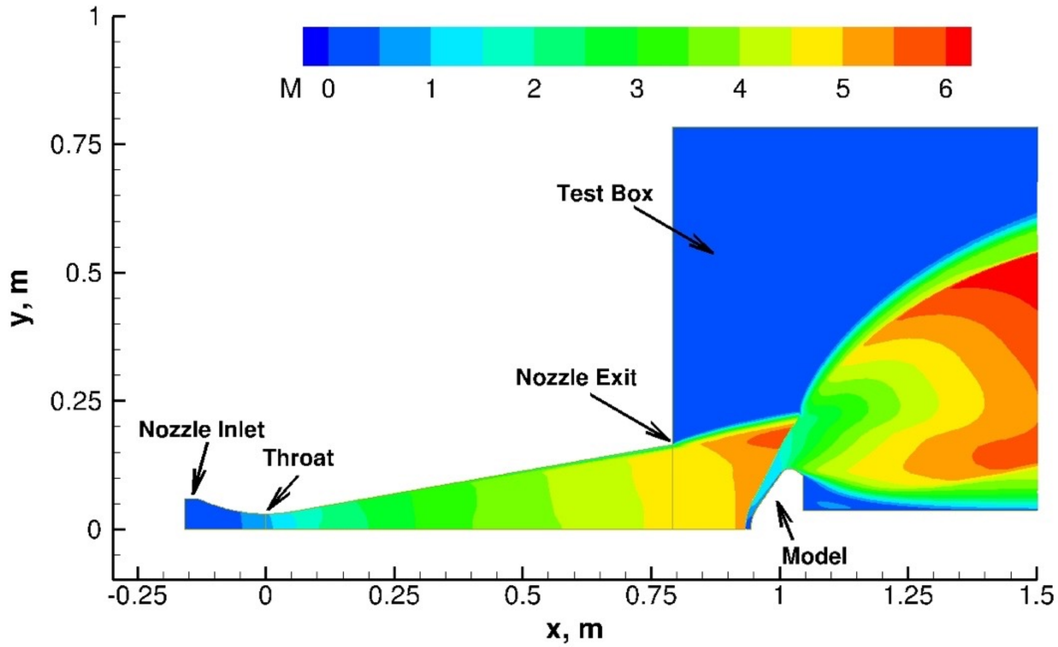


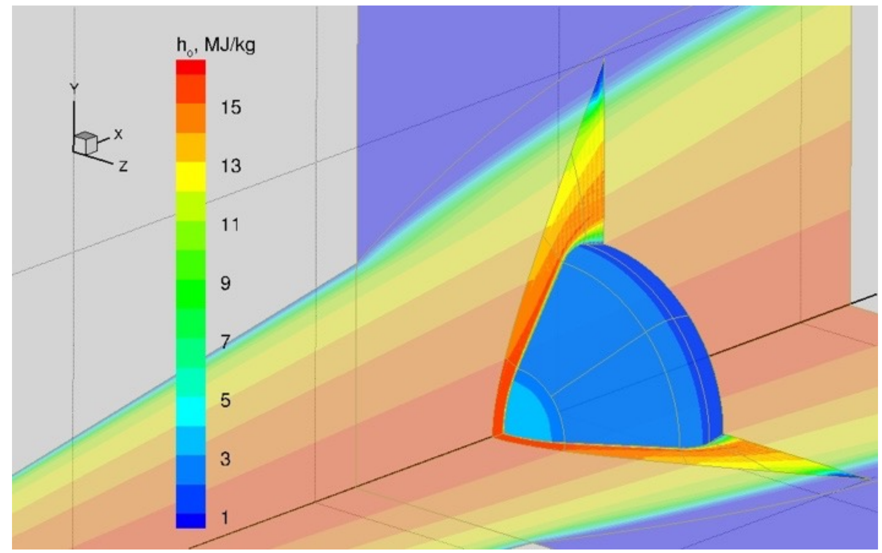
23.6-cm 55° sphere-cone calorimeter model: 6 Gardon heat flux and 5 pressure gages

10.2-cm iso-q slug calorimeter

10.2-cm iso-q Gardon gage calorimeter

Computational Approach





- CFD analysis includes simulations of the nonequilibrium flowfield in the facility nozzle and test box, including the model flowfields
- Prescribe flow profiles at the nozzle inlet with chemical equilibrium composition
- Axisymmetric or 3-D Navier-Stokes equations with nonequilibrium processes
- Thermochemical model for arc-jet flow
  - Six chemical species: N_2, O_2, NO, N, O, Ar
  - Two-temperature model (Park): T -translational-rotational, T_v -vibrational-electronic
- Data-Parallel Line Relaxation Method - DPLR Code

Presentation of Results

- One example from simulations of IHF 13-inch nozzle flow including the test box and 55° sphere-cone model

- Flow characterization and calorimeter model simulations
  - Diffuser flow-capture issues (wooden sphere-cone model blockage tests, IHF 345)
  - 10.2-cm iso-q slug calorimeter simulations used to determine centerline total enthalpy (in the paper)
  - 23.6-cm Gardon gage calorimeter model simulations and comparisons with heat flux and pressure measurements (one condition, other two in the paper)

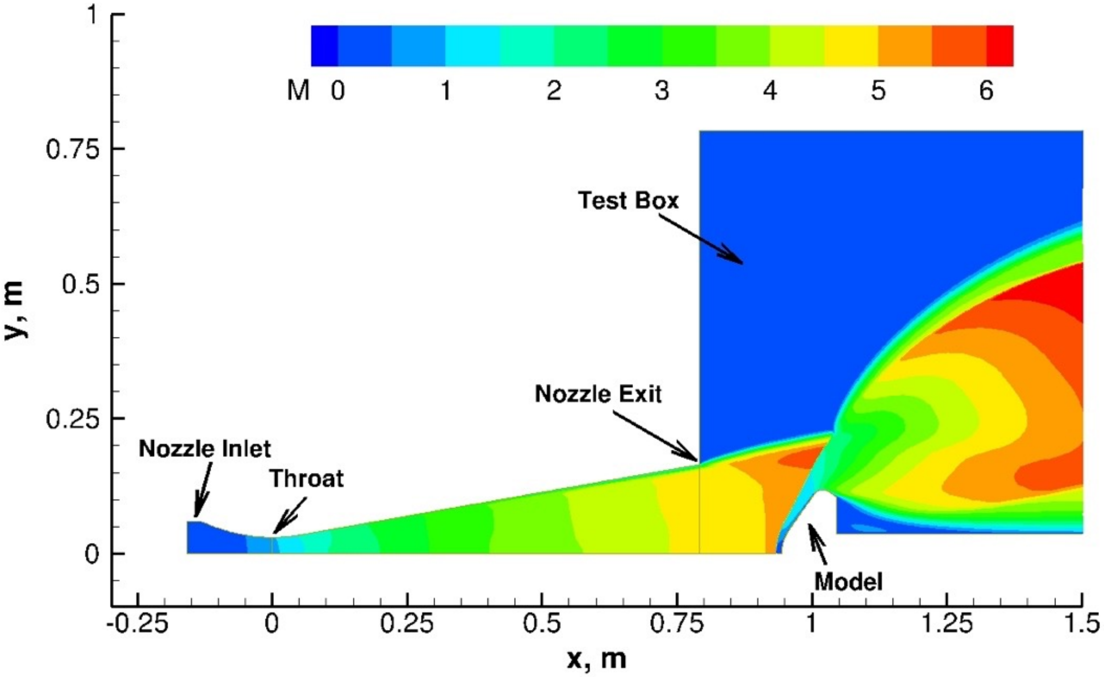
- Effects of the sphere-cone model shape change are assessed for one case (IHF 352, condition 2)

- Simulations of the 55° sphere-cone model with manufactured surface features
  - Smooth surface, one with a transverse fence, and one with a gap
  - Qualitative comparisons with HD video and infrared camera images

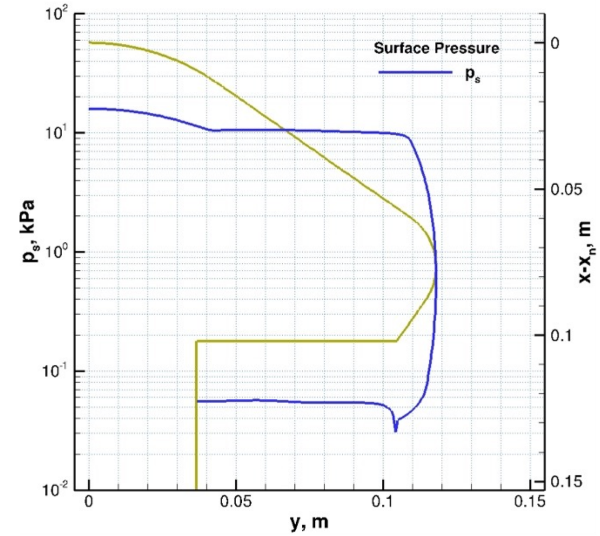
For three conditions of IHF 345 and IHF 352 tests, details of facility conditions, calorimeter data, corresponding CFD estimates, and comparisons with the measurements are all reported in the paper.

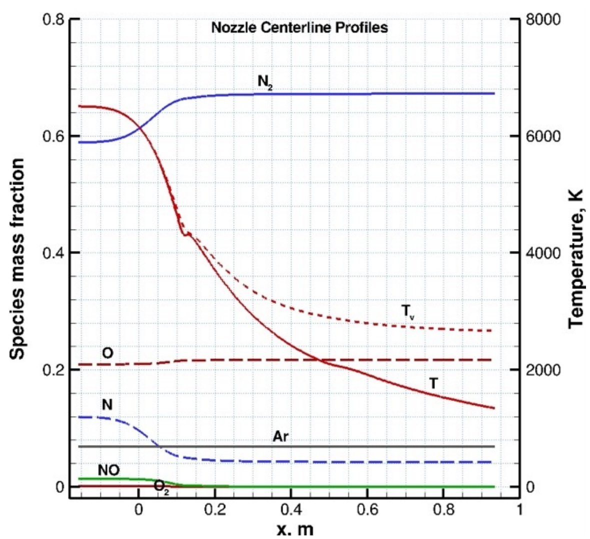
Example: 55° Sphere-Cone Model Simulation Results

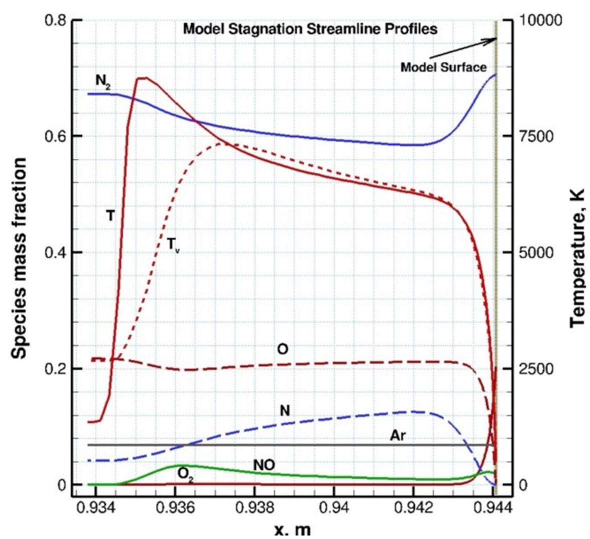
IHF 13-inch nozzle: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar, p_{box} = 2 torr



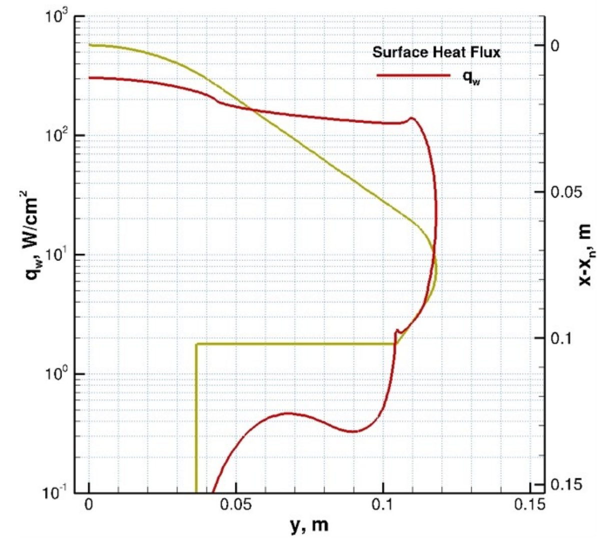
surface pressure







surface heat flux

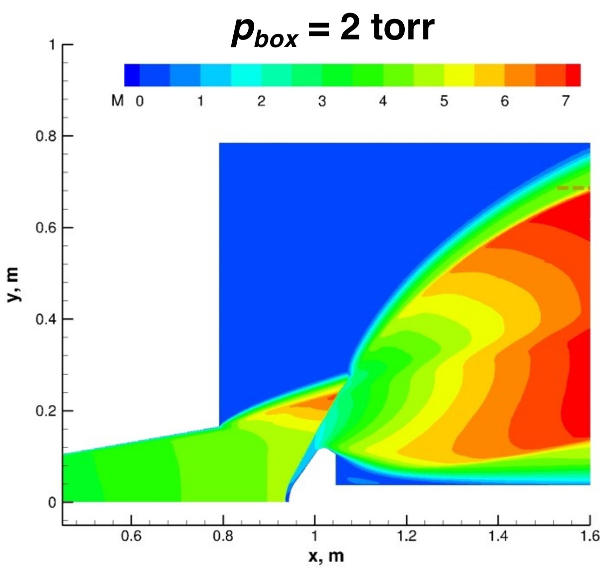


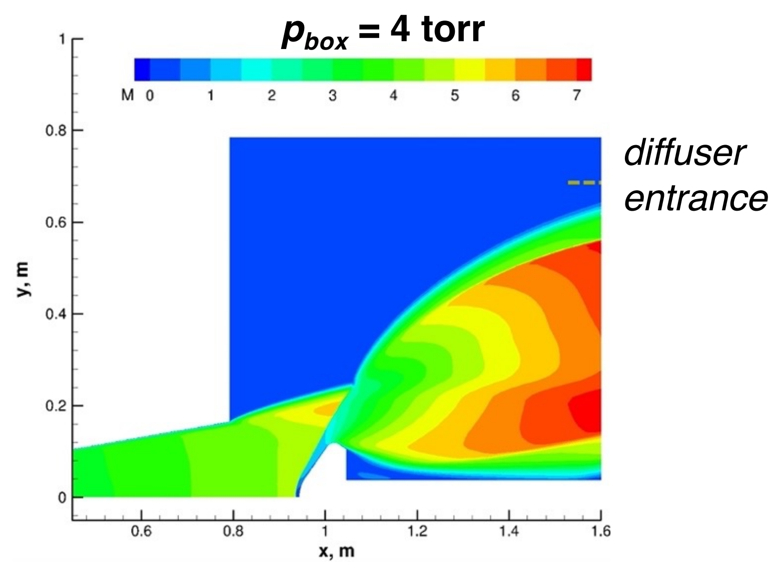
Diffuser Flow Capture Issues and Blockage Tests

23.6-cm Diameter, 55° Sphere-Cone Model

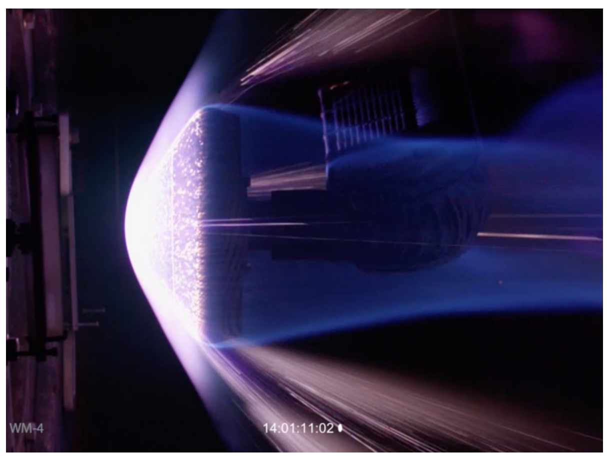
IHF 13-inch nozzle flow: $\dot{m}$ = 849 g/s, h_{ob} = 22.3 MJ/kg, h_{ocl} = 23.7 MJ/kg, parabolic profile, 6.4% Ar

CFD Results Test Box





Blockage Test



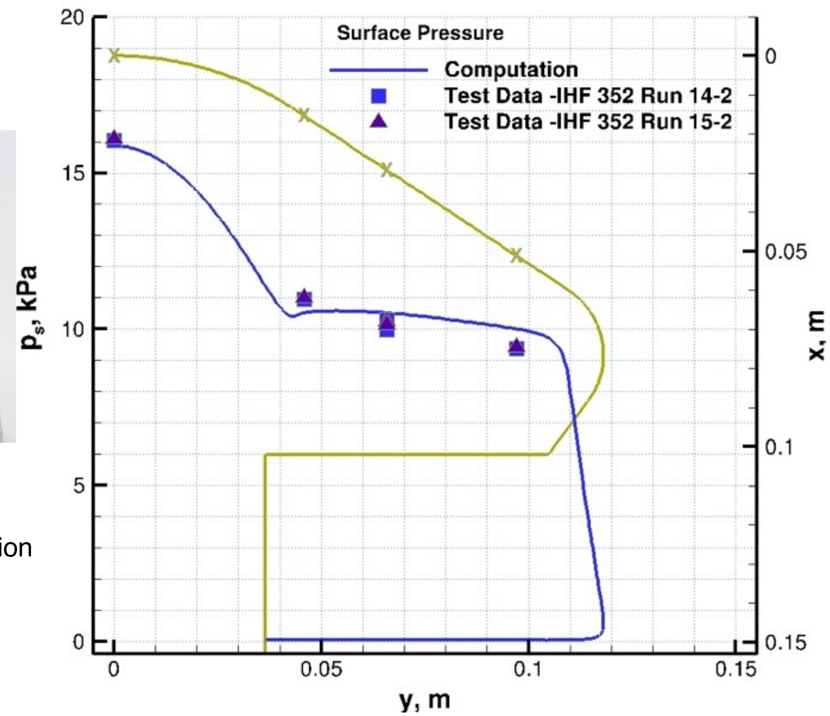
IHF 345, Run 3-1
x_{ml} = 15.24 cm (3.5 torr)

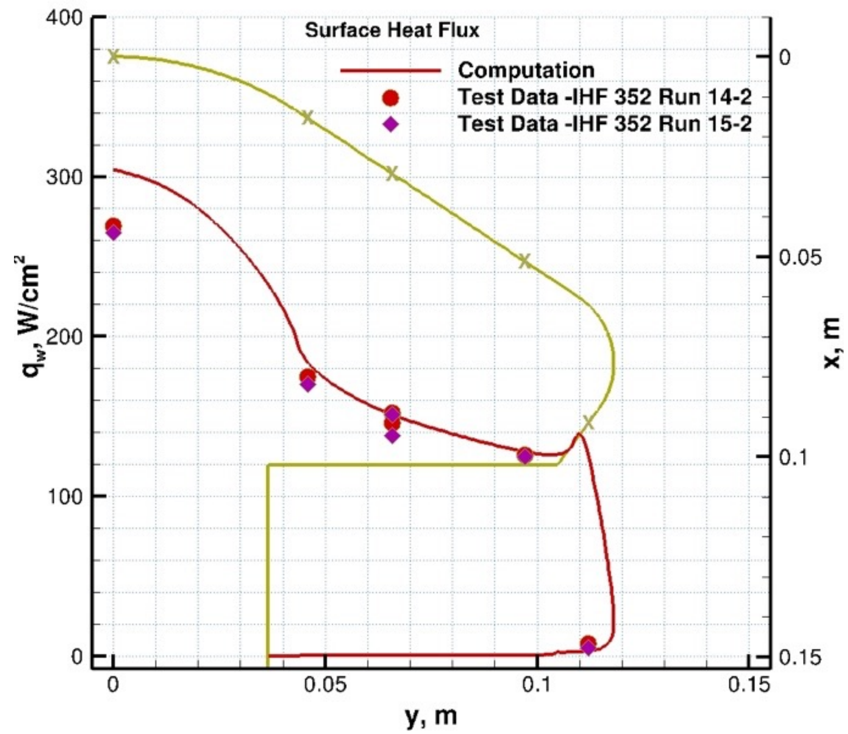
- One of the challenges in testing relatively large models is the possibility that the model flowfield may not be captured by the diffuser, potentially degrading the test flow
- CFD results show that the flow is not captured at test box pressure of 2 torr or less (spillage); but it is captured at 4 torr, and the flow quality is still acceptable for testing
- Previous test anomaly in this nozzle with a similar sized article led to blockage tests with wooden models, confirming the flow capture at 3.5 torr box pressure

Comparison of CFD Results with 55° Sphere-Cone Calorimeter Data

IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar

Q_2 and p_2 at the same radial location as Q_4 and p_4 but at opposite side of the flank section



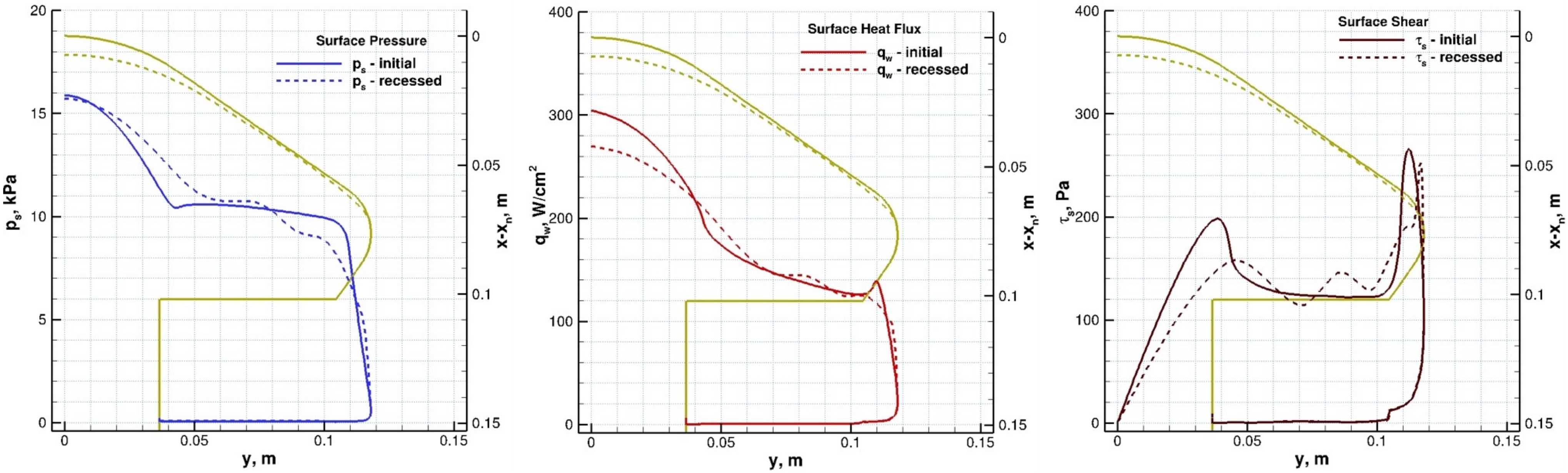


- *X* symbols on the model surface profile represent radial locations of the gages
- For this case, CFD results are in good agreement with both pressure and heat flux data (except Q_1 value at stagnation point is 11.5% lower)
- The heat flux measurements are estimated to be accurate to within ±15% and the pressure measurements to within ±5% (based on historical NASA Ames facility data)
- Agreement in the surface pressures at the stagnation point and three locations on the conical flank indicates that wave interaction effects from the nozzle exit are adequately captured
- Both pressure and heat flux measurements at opposite sides of the flank section (p_2 and p_4, Q_2 and Q_4) do not indicate any asymmetry with respect to the symmetry plane

Comparisons of Initial and Recessed Surface Quantities

55º Sphere-Cone Model (recessed model ID: 44029-25, IHF 352 Run 8, cond 2, 80 s)

IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar

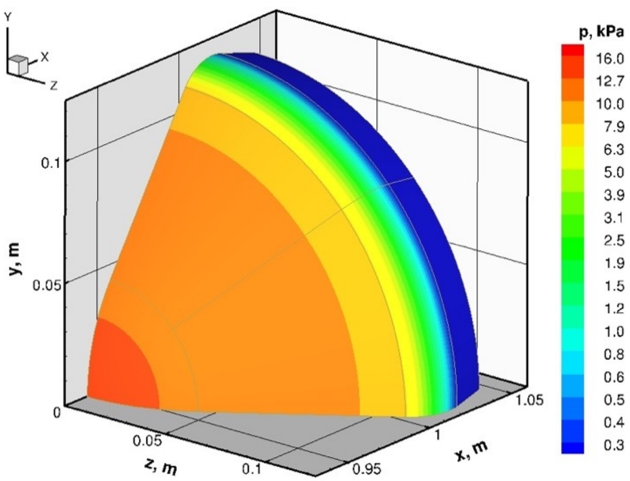


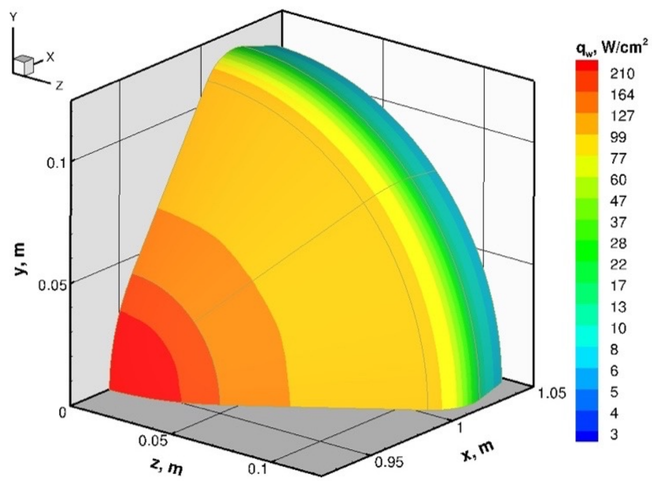
- One of the concerns in testing with the sphere-cone model configuration is that the test article ablation and its subsequent shape change may make interpretation of the test data more difficult
- Recessed geometry is a least-squares-fit to the forebody profile obtained from manual recession measurements
- Effective nose radius of the recessed model is larger, as a result, the computed stagnation-point heat flux is reduced by 11.4%
- Computed surface heat flux values on the flank section are relatively unaffected for this case (pressure and shear are more sensitive to the shape change)

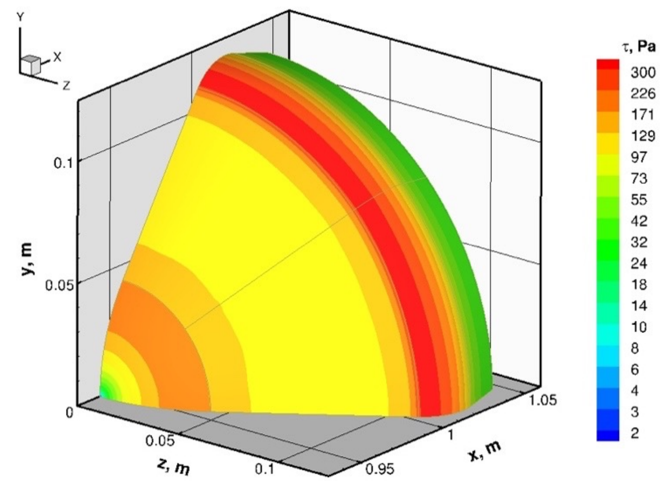
Computed Surface Contours and Symmetry Plane Profiles

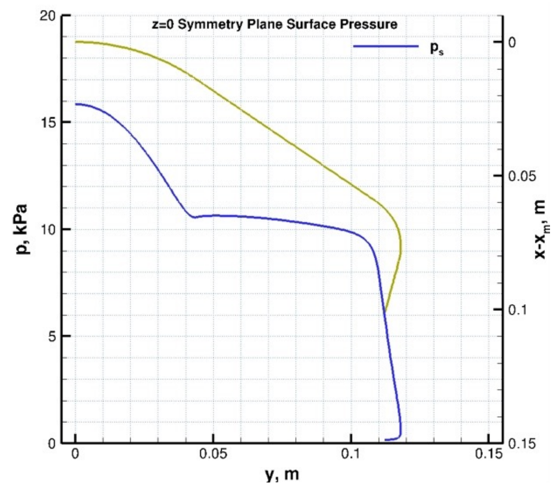
55° Sphere-Cone Model –Smooth Surface

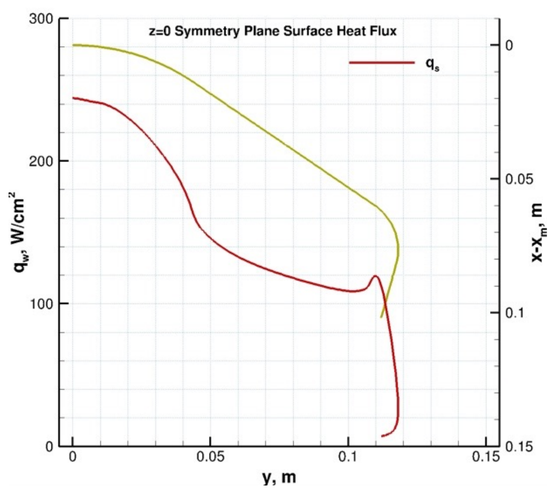
IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar

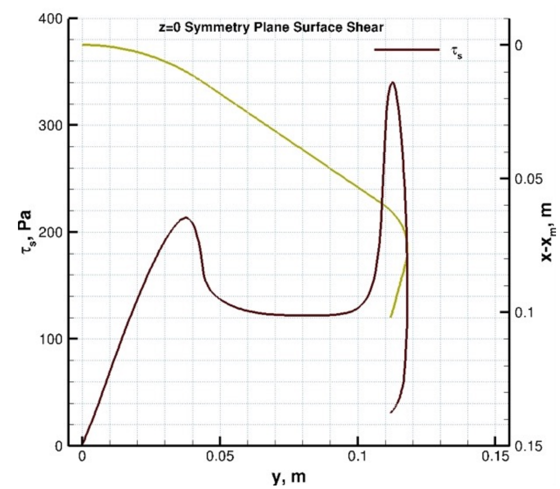










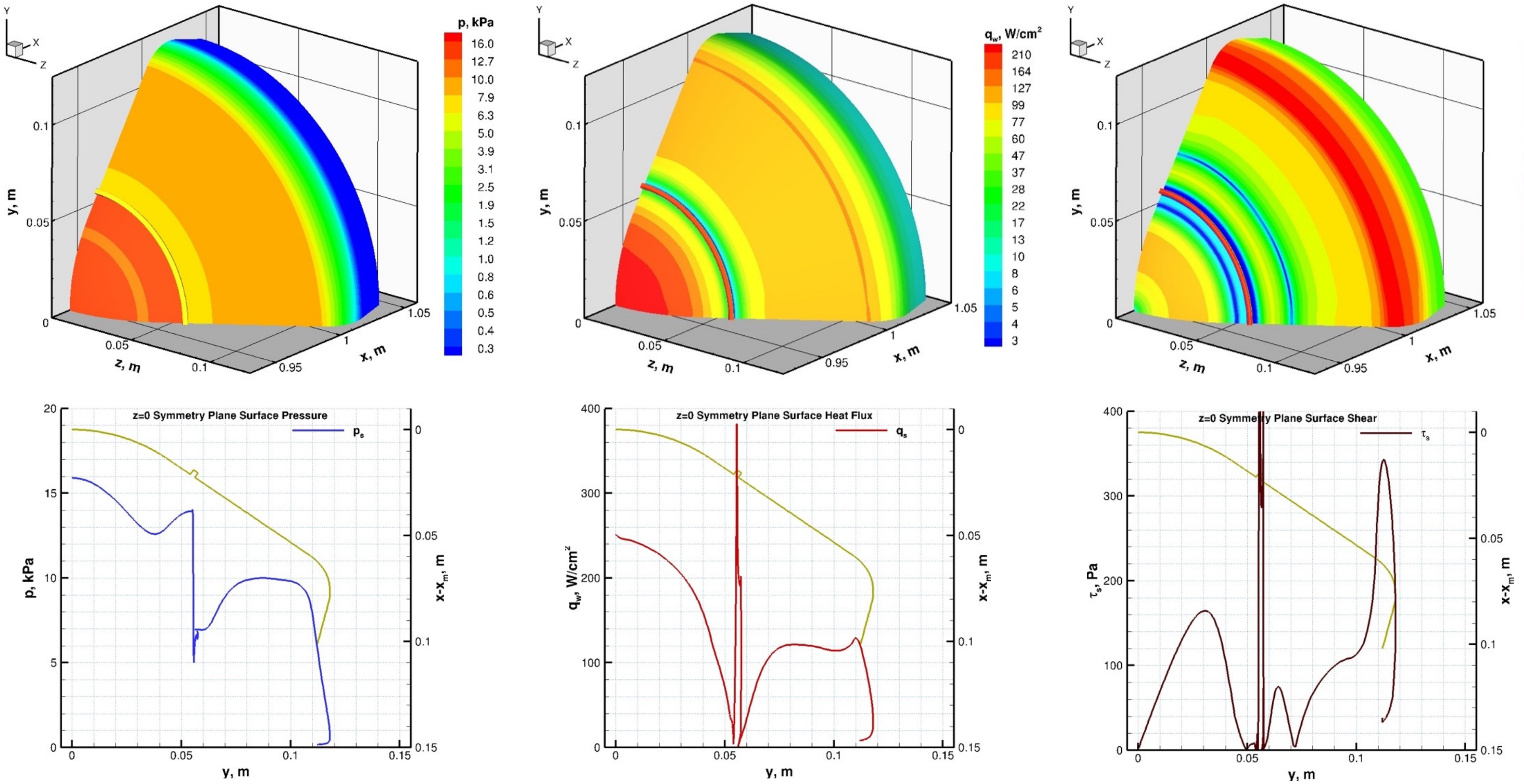


- Smooth surface simulations are for test articles with no seams or ones with flush seams
- Surface heat flux is calculated using fully catalytic wall and radiative equilibrium BC
- The conical flank section is considered as the test section of the model where surface features (seams, fences and gaps) and instrumented thermocouple plugs are placed

Computed Surface Contours and Symmetry Plane Profiles

55º Sphere-Cone Model –with Manufactured Fence

IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar



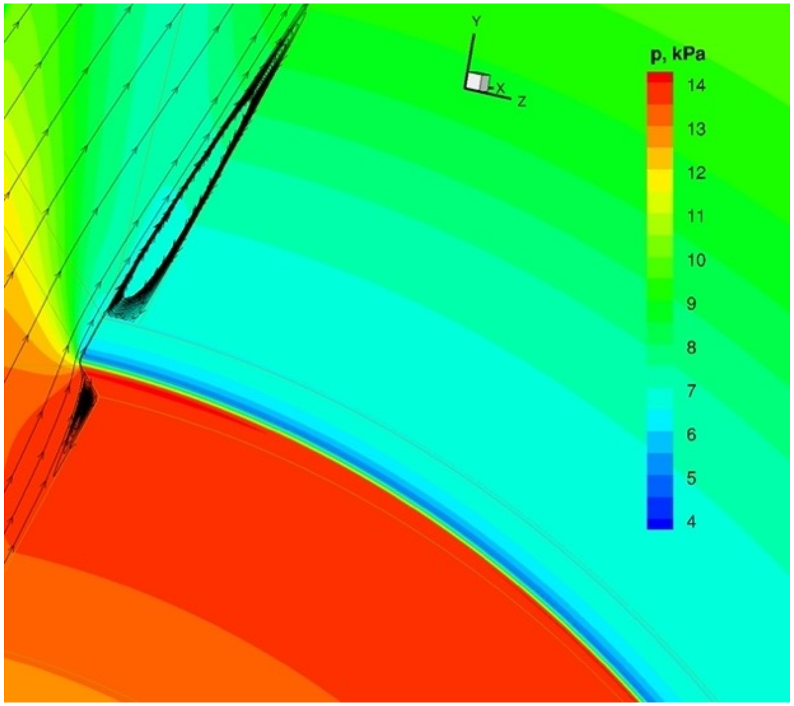
- Influence of the fence on both upstream and downstream model surface quantities is well beyond the local region near the fence: both the nosecap and entire flank section are affected
- Computed shear contours and line plot show all stagnant and separated regions in the flowfield (e.g., blue sections for stagnant regions)
- Increased shear and heat flux values on the flank section are indicative of the flow reattachment

Computed Flowfield and Surface Contours of Fence Region (near x-y symmetry plane)

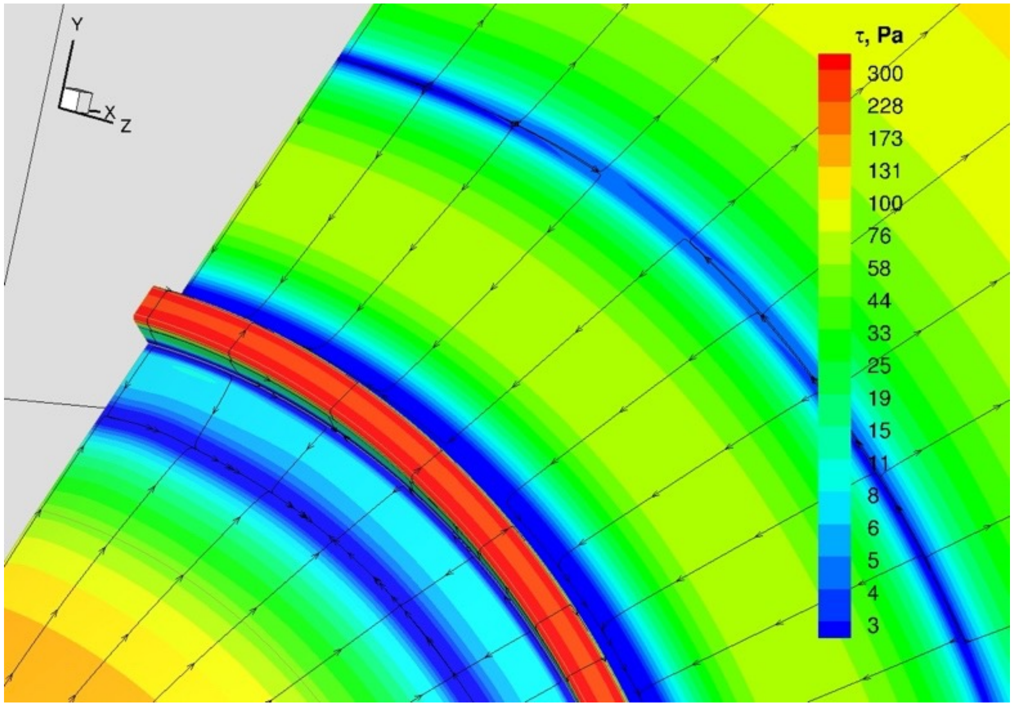
55º Sphere-Cone Model –with Manufactured Fence

IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar

pressure with streamlines



surface shear with streamlines

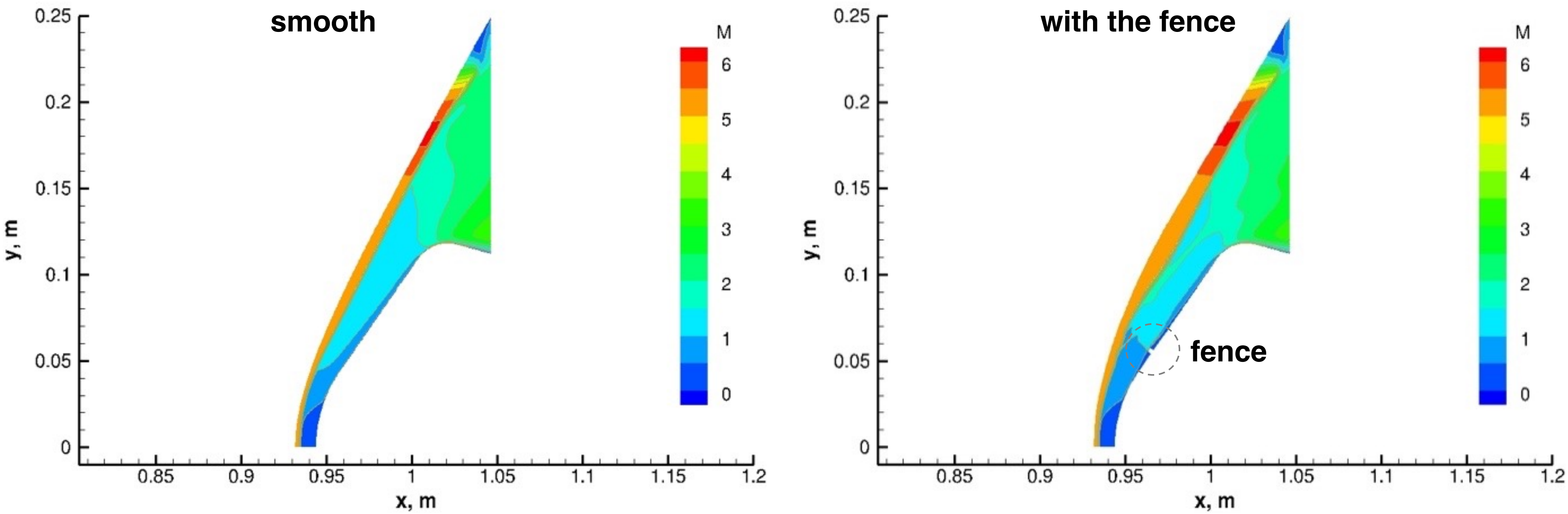


- The surface and symmetry plane pressure contours with streamlines are shown on the left: a primary separation bubble is formed at the fence leading edge, which interacts with the oncoming subsonic boundary layer; as the flow goes over the fence and expands, another separated region is formed right behind the fence (a backward facing step).
- The surface shear contours with surface streamlines on the right clearly show the two separated flow regions near the fence and subsequent flow reattachment

Effects of Fence on Model Flowfield –Mach Number Contours

55° Sphere-Cone Models: Smooth and One with Manufactured Fence

IHF 13-inch nozzle flow: $\dot{m}$ = 451 g/s, h_{ob} = 13.1 MJ/kg, h_{ocl} = 15.4 MJ/kg, parabolic profile, 6.9% Ar

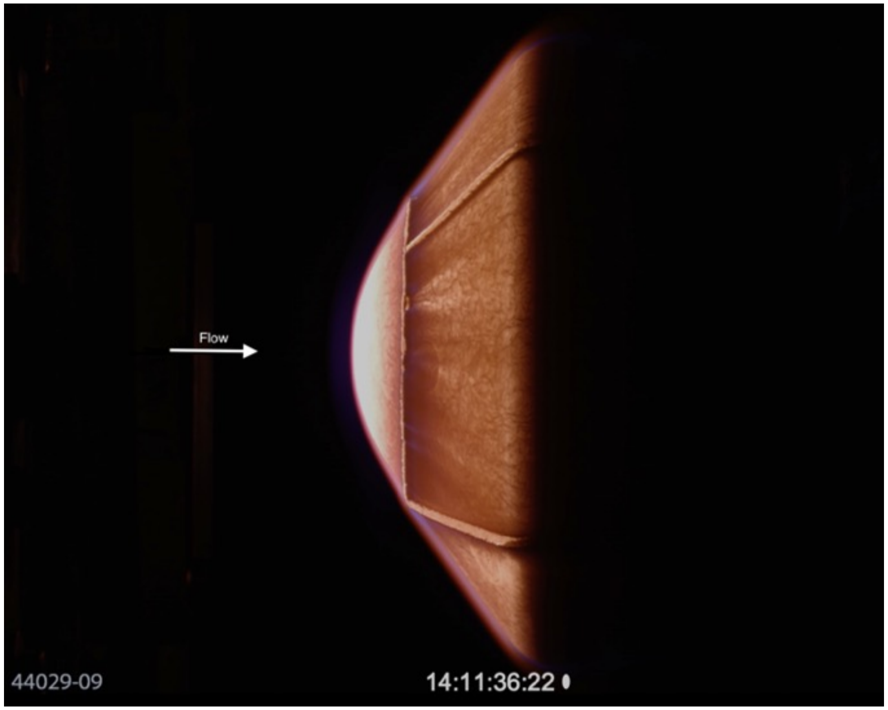


- **Smooth:** At the start of the conical flank section, boundary layer edge Mach number is subsonic but most of the shock layer remains supersonic, the sonic line attachment being near the shoulder
- **Model with the fence:** The sonic line moves to the fence leading edge, and the entire shock layer region up to the fence becomes subsonic (shock wave is pushed away from the body as the flow is more compressed); As the flow passes the fence, it becomes supersonic, and expansion waves are generated, and their interactions with the model shock wave effectively pull the shock wave towards the body on the conical flank section

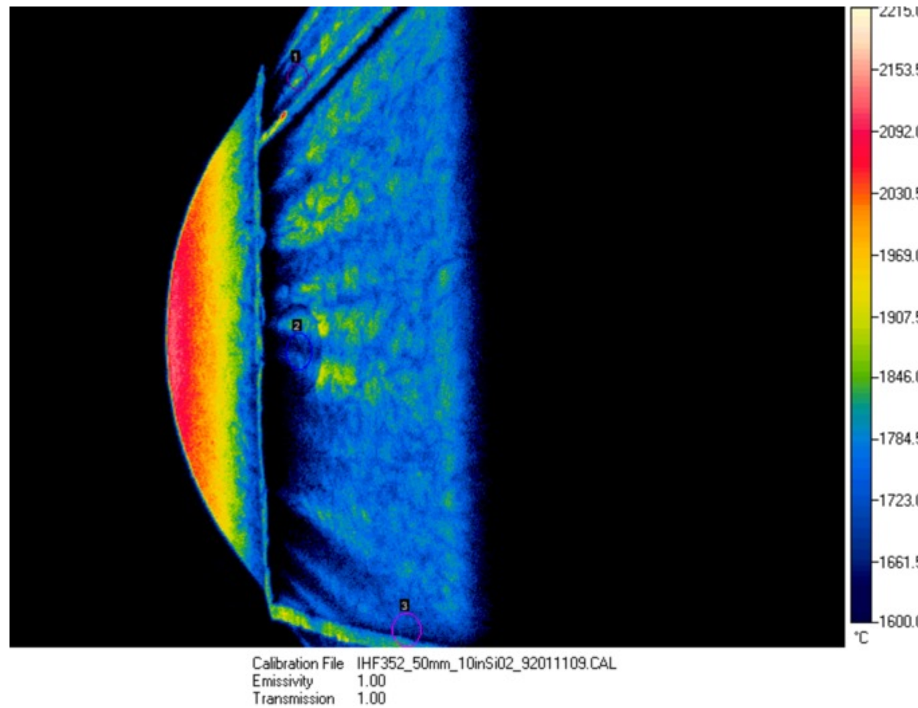
Qualitative Images of 55º Sphere-Cone Test Article with Fences

(IHF 352, Run 7, condition 2)

HD video camera



IR camera

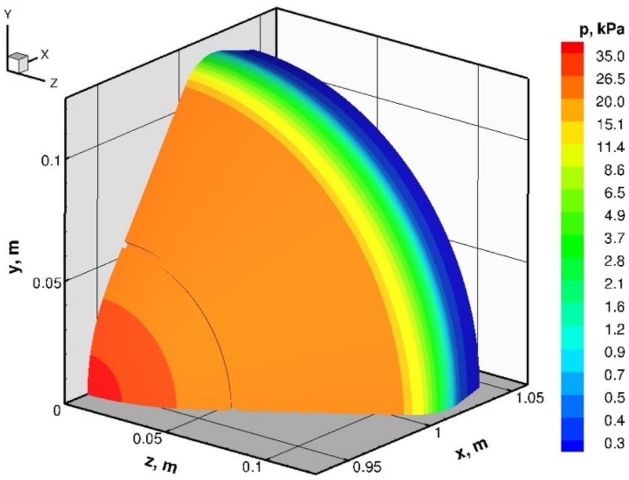


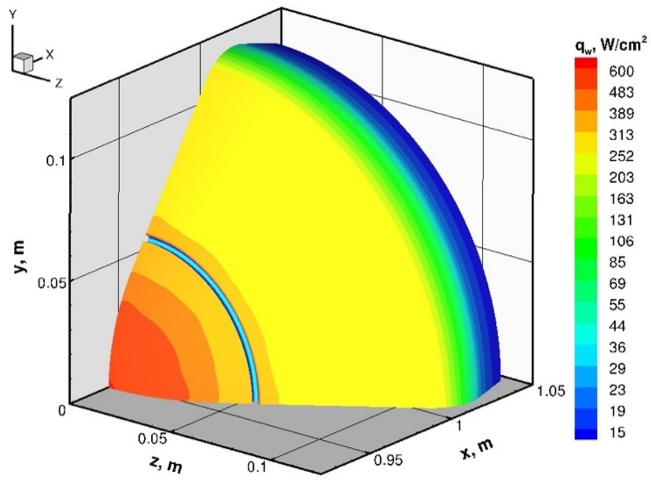
- These images, provided as qualitative test data, were taken right before the manufactured fences started to ablate
- The dark regions on the model surface at both upstream and downstream of the fence perpendicular to the flow direction are indicative of relatively cold separated flow regions
- These images provide qualitative heating distributions, which are like the CFD-predicted surface heat flux contours shown earlier
- The test article has several manufactured fences, while the fence perpendicular to the flow direction is the only one modeled in the CFD simulations

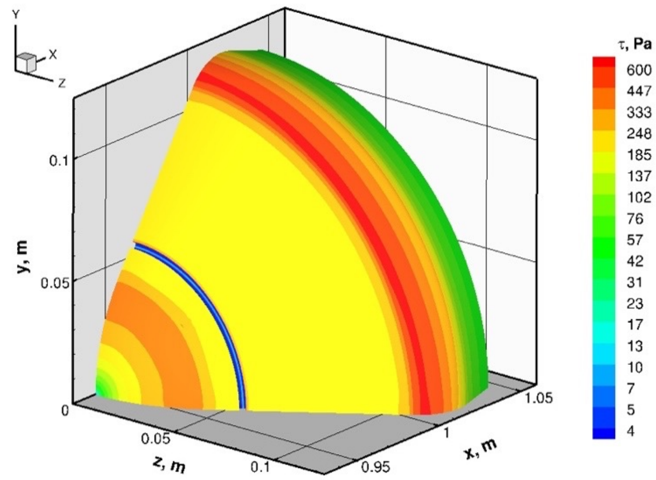
Computed Surface Contours and Symmetry Plane Profiles

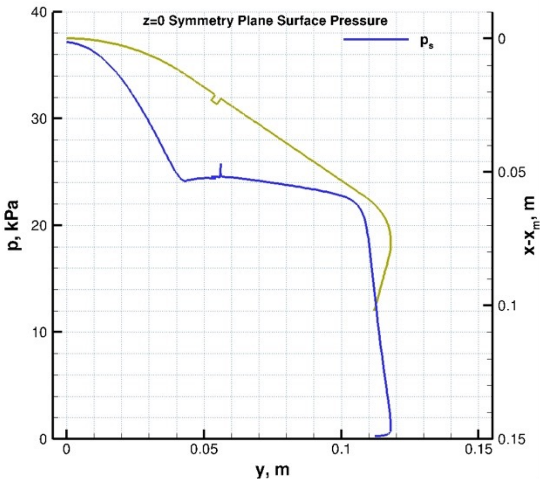
55° Sphere-Cone Model –with Manufactured Gap

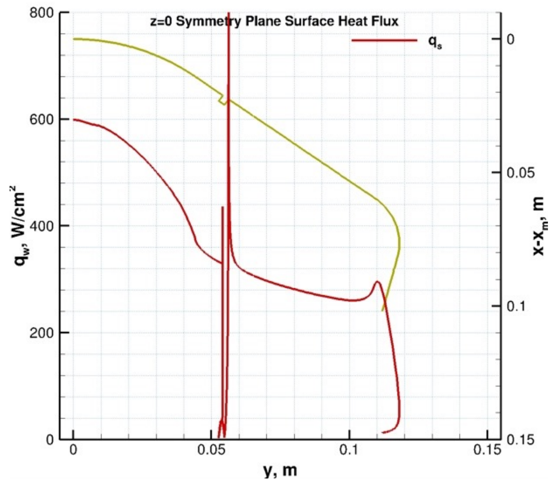
IHF 13-inch nozzle flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.9 MJ/kg, h_{ocl} = 22.1 MJ/kg, parabolic profile, 6.4% Ar

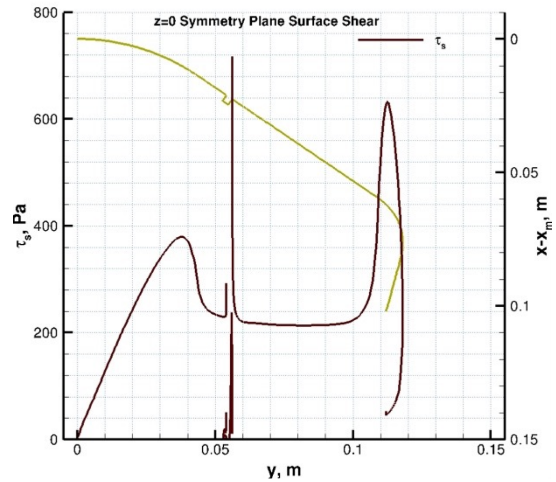












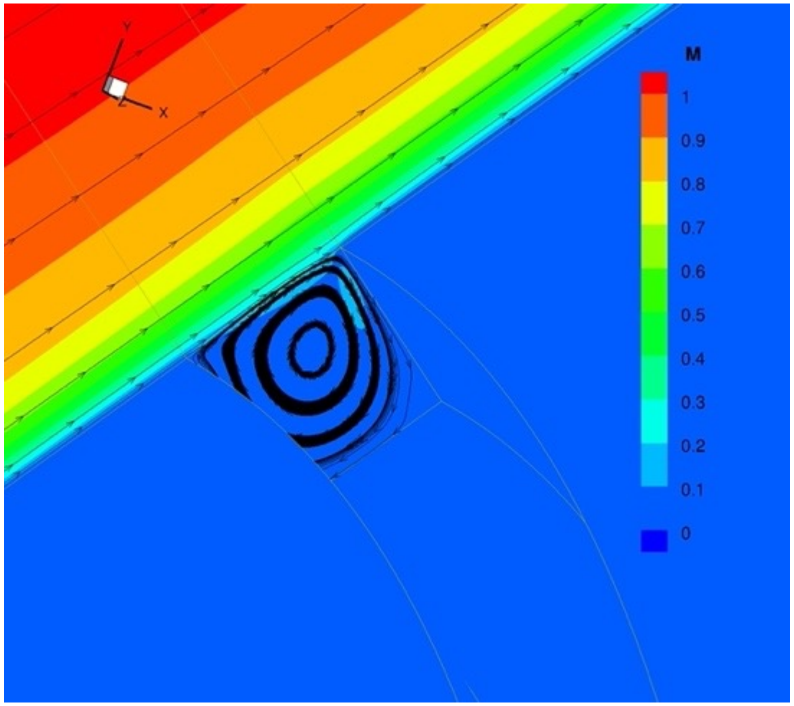
- Even though the presence of the gap disturbs the flow over the model, its effects remain relatively local, just upstream, and downstream of the gap
- Oncoming flow separates at the gap leading edge, but it does not attach to the gap floor
- Computed surface heat flux and shear values at the bottom floor of the gap are significantly lower than those upstream of the gap

Computed Flowfield and Surface Contours of Gap Region (near x-y symmetry plane)

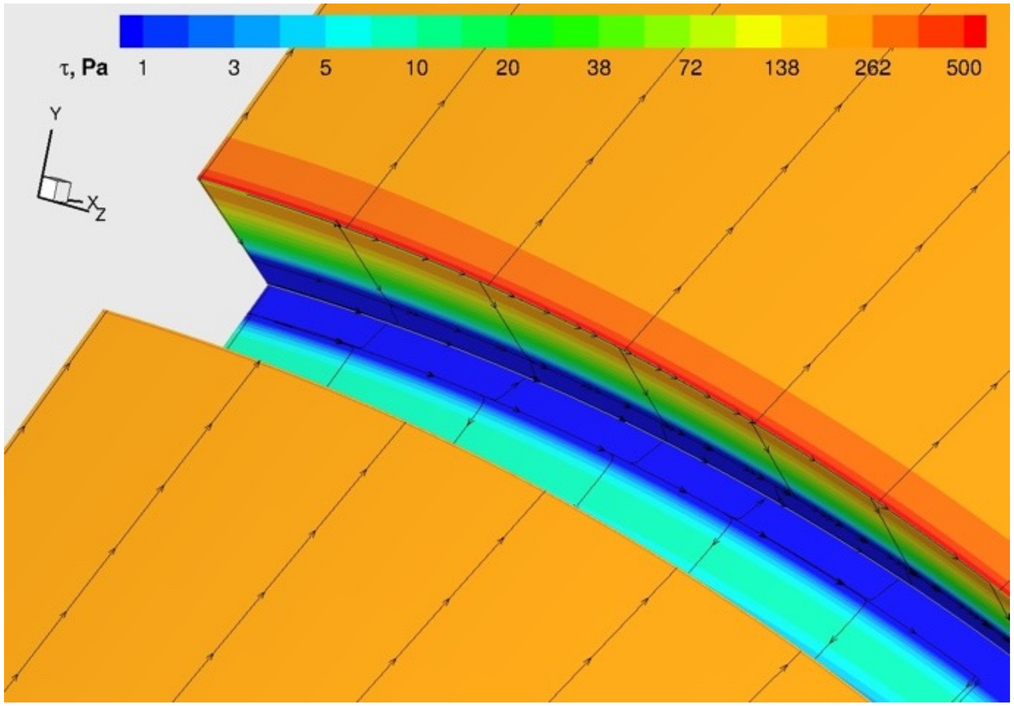
55º Sphere-Cone Model –with Manufactured Gap

IHF 13-inch nozzle flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.9 MJ/kg, h_{ocl} = 22.1 MJ/kg, parabolic profile, 6.4% Ar

Mach number with streamlines



surface shear with streamlines

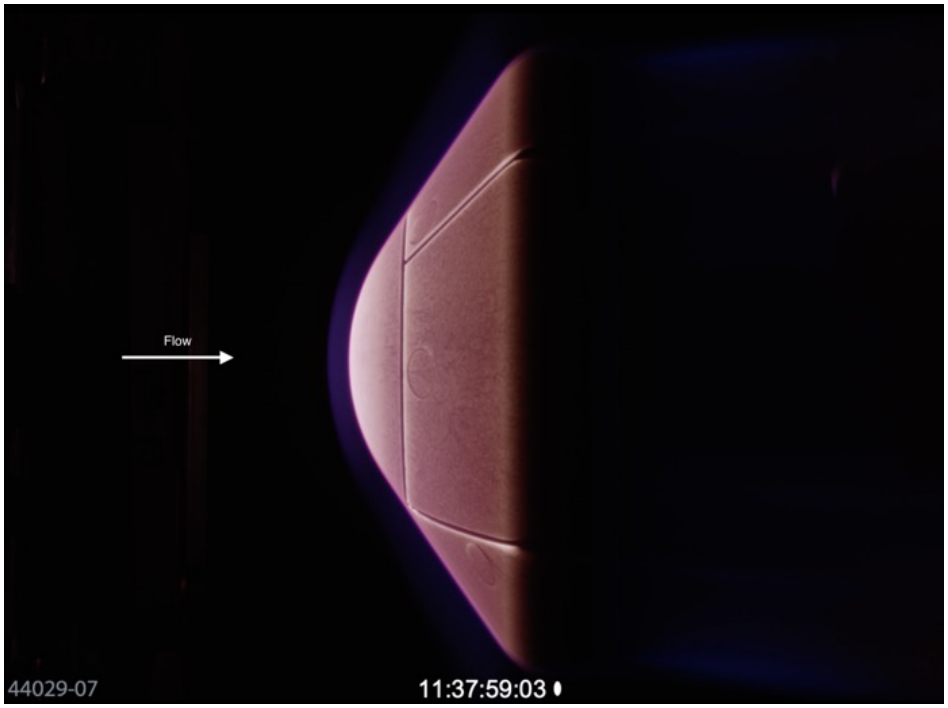


- Mach number contours with streamlines shown on the left indicate that the oncoming flow goes through an expansion at the gap leading edge, which is followed by a flow separation, and a recirculation region inside the gap is formed
- The shear contours and surface streamlines on the right provides insight into the recirculating flow patterns within the gap: since the flow does not attach to the gap floor, computed surface shear and heat flux values at the gap floor are significantly lower than those upstream

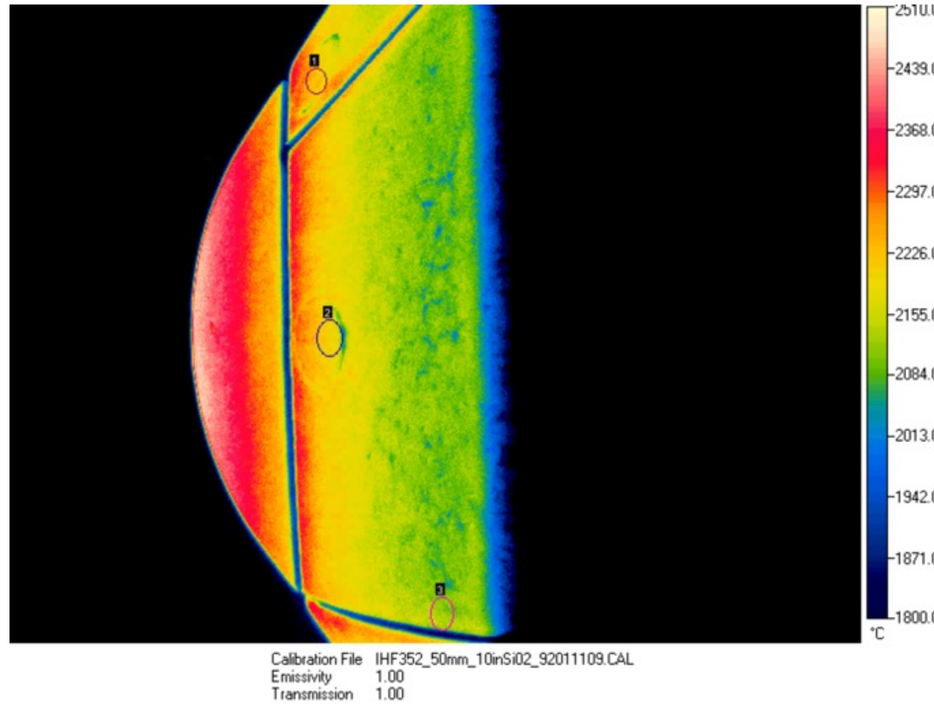
Qualitative Images of 55° Sphere-Cone Test Article with Gaps

(IHF 352, Run 6, condition 1)

HD video camera



IR camera



- These images, provided as qualitative test data, were taken before the test article started to ablate
- The dark or blue regions inside the gap perpendicular to the flow direction indicate colder surface conditions, while the bright spots or red regions just downstream of the gap show augmented heating locations
- These images and the CFD-predicted surface heat flux contours shown earlier are in reasonable qualitative agreement
- The test article has several manufactured gaps but only the transverse gap is considered in the CFD simulations

Summary and Concluding Remarks

- Computational simulations in support of 23.6-cm diameter, 55° sphere-cone model tests in the NASA Ames 60-MW Interaction Heating Facility are presented
  - Tests were conducted with the model placed in a free jet downstream of the 33.0-cm diameter conical nozzle
  - Some models included surface features such as manufactured fences and gaps
  - Calibration data were obtained using stagnation slug calorimeters and a sphere-cone calorimeter model–with the same geometry as smooth surface test articles–instrumented with six Gardon heat flux gages and five pressure sensors

- Through comparisons with the calibration measurements, CFD simulations provide estimates of the arc-jet test environment parameters that are needed to evaluate the performance of thermal protection system materials
  - Estimated parameters include centerline total enthalpy, surface shear, hot-wall heat flux, boundary layer thickness, and boundary layer edge Mach number
  - The sphere-cone calorimeter provides a dataset to compare against the computed surface pressure and heat flux values and their distributions
  - For test articles with surface features, CFD simulation is the only tool to estimate surface pressure and heat flux distributions

- CFD simulations, when supported with the experimental evidence, define arc-jet test environments along with valuable insights and provide an important framework for tracing a TPS material performance from a ground test facility to flight

Acknowledgments

- The authors would like to thank **Parul Agrawal** for her help in planning of IHF 345 and IHF 352 test series, **Keith Peterson** for his help in running IHF 352 tests, and the TSF test engineers involved in these tests, **Frank Hui**, **Enrique Carballo**, and **Imelda Terrazas-Salinas**.

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